

Article

Media-Free and Contactless Micro-Positioning System Using Ultrasonic Levitation and Magnetic Actuators

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Abstract

In micro-production technology (MPT), the demand for ultra-precise machine tools has been steadily increasing. Conventional guideway systems, such as hydrostatic or aerostatic bearings, often face limitations in terms of compactness, media supply, and susceptibility to external disturbances, which restrict their applicability in next-generation precision manufacturing. In order to address these challenges, this paper presents a novel media-free, contactless, and active three-degree-of-freedom (DOF) planar positioning (guiding) system that integrates ultrasonic actuators with electromagnetic actuators. The hybrid concept combines the high load capacity and self-stabilization of double-acting ultrasonic actuators and pronounced controllability of the electromagnetic actuators. A prototype system was developed and experimentally validated. Ultrasonic actuators successfully established a stable levitation state, while electromagnetic actuators provided fine adjustment of the levitation height in the micrometer range. Load tests demonstrated that the system maintained stable levitation under an external load of 30 N. These results confirm the feasibility of the proposed approach for robust and precise positioning. The developed hybrid system therefore represents the potential for next-generation precise manufacturing machines in MPT, offering high accuracy and robustness against external disturbances.

Keywords: micro-production technology; micro-positioning system; double-acting ultrasonic actuator; electromagnetic actuator



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1. Introduction

Micro-electro-mechanical systems (MEMSs) have become essential components in numerous modern applications, particularly in miniaturized sensors for smartphones, vehicles, and other consumer products [1]. The continuous market growth in this field [2] has increased the demand for more efficient and highly productive MPT. Achieving both high precision and productivity with MPT, however, remains a major challenge for micro-manufacturing machines. Current micro-manufacturing machines are mostly derived from downscaled macro-machine concepts [3], but this approach reveals significant drawbacks. They suffer from large energy consumption and high space requirements, inefficient miniaturized drives, and the stick-slip effect [4], which cause severe precision losses. A critical limiting factor is the guidance system of micro-manufacturing machines, which directly determines positioning accuracy, stability, and system efficiency.

Conventional hydrostatic and aerostatic guidance systems are widely used in precision engineering [5,6]. Although they have no stick-slip effects and high precision, they still

exhibit distinct disadvantages. Hydrostatic systems require continuous media supply and return, risk contamination [7], and demand large installation space. Aerostatic systems do not require a media return, but suffer from low stiffness and poor damping [8]. These drawbacks restrict their applicability in next-generation MEMS manufacturing, where compactness, cleanliness, and high-micrometer-level accuracy are required. Magnetic guides in precision engineering offer the advantages of no friction losses and the absence of stick-slip effects as well as wear [9]. Their drawback is their unidirectional force generation, which necessitates mechanical wrap-around structures, leading to complex and bulky machine designs [10]. To overcome these limitations, this research presents a novel hybrid planar positioning system that combines ultrasonic actuators with magnetic actuators. Ultrasonic levitation offers high load capacity and self-stabilizing behavior due to its double-acting operating principle, while magnetic actuators provide stiffness, controllability, and precise disturbance rejection. Compared with the studies by [11–13], the main novelty of the present work stems from the design and integration of a double-acting ultrasonic actuator. In previous works [11–13], the ultrasonic actuators were single-acting and rigidly mounted to the supporting frame. In contrast, the new double-acting UA developed in this paper features two active output-surfaces, which generate levitation forces on both sides and thus enable self-stabilizing behavior without requiring mechanical alignment or rigid fixation. Moreover, the actuator in this paper is coupled to the prototype frame via an air gap and four tension ropes, effectively avoiding direct mechanical contact and significantly reducing vibration transmission to the structure.

In Section 2, the actuator structures are presented. This includes a detailed description of the ultrasonic actuator, the magnetic actuator, and their integration into a hybrid actuator. Section 3 introduces the control principle and the experimental setup. The performance of the developed hybrid planar positioning system is then demonstrated and discussed in Section 4.

2. Concepts and Structures of Actuators

2.1. Concept of Hybrid Actuator

The adjustable hybrid actuator integrates an ultrasonic actuator (UA) and a magnetic actuator (MA) (Figure 1a). While the UA generates the levitation force required for contactless operation, the MA provides the counteracting magnetic preload force. As shown in Figure 1b, the ultrasonic actuator is flexibly fixed by four high-tensile-strength ropes. This mounting method restricts in-plane motions (X- and Y-directions) while allowing for small movement in the vertical direction (Z-direction). In the following sections, the structural design and operating principle of each actuator are introduced in detail.

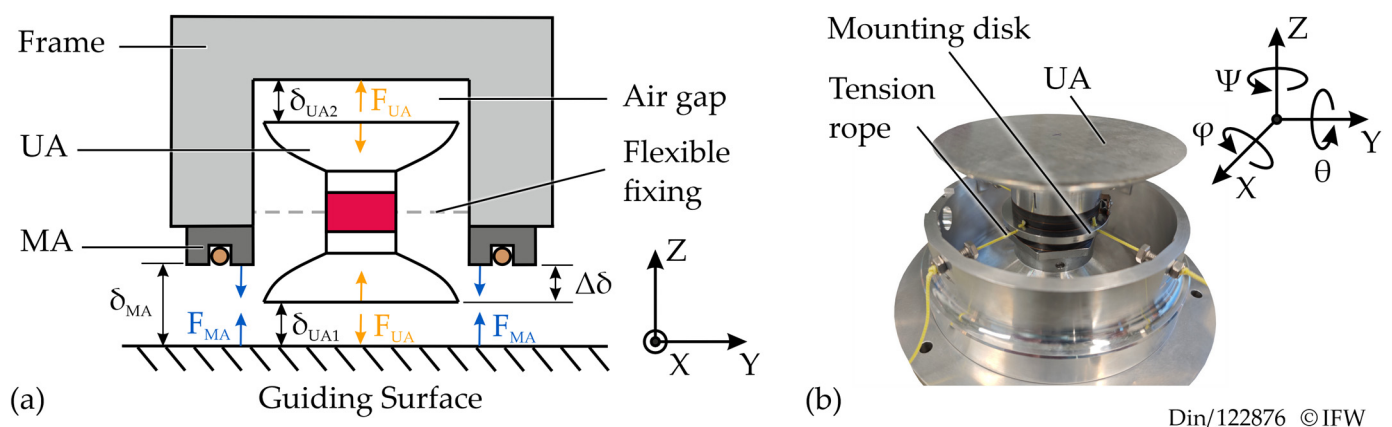


Figure 1. (a) Concept of hybrid actuator, (b) flexible fixing of UA using tension ropes.

2.2. Structure of Ultrasonic Actuator

Based on the squeeze-film effect, a double-acting UA (the related parameters are listed in Table 1) with two large output surfaces was designed and manufactured in-house at the Institute of Dynamics and Vibration Research (IDS) in Hannover, Germany [14], as shown in Figure 2a. It has a symmetrical design and creates overpressure in the air gaps on both end surfaces to achieve levitation. Because of the double-acting principle of the UA, precise and self-stable positioning is achieved without elaborate alignment measures. The UA has a diameter of 120 mm and a length of 85.2 mm. The larger levitation surface offers increased levitation force compared to the actuator reported in [11,13].

Table 1. Parameters of the piezoelectric material in UA.

Material	PIC181 (from PI Ceramic GmbH, Lederhose, Germany)
Density	7800 kg/m ³
d_{33}	2.65×10^{-10} C/N
Quality factor	2000
Dielectric loss factor	3×10^{-3}

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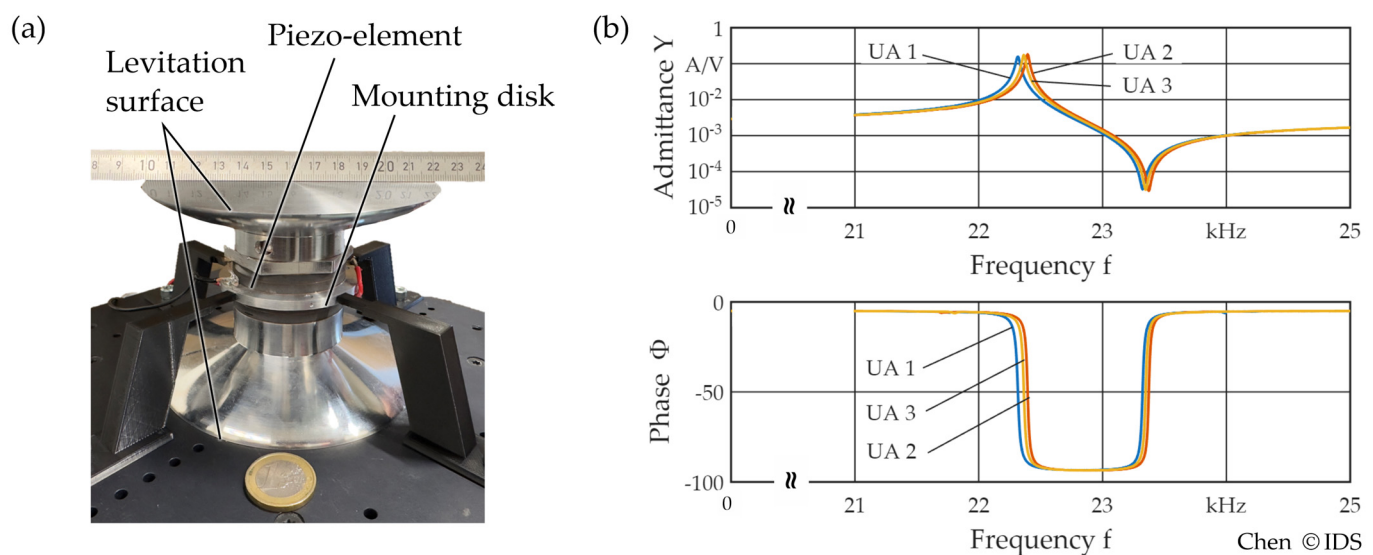


Figure 2. (a) Double-acting UA, (b) electrical frequency responses of three manufactured UAs.

Three identical UAs were fabricated and arranged in a triangular configuration for testing in the positioning system. This arrangement with three actuators represents the minimal number required to control the vertical displacement and tilting motions (z , φ , θ) of the platform without creating an overdetermined system and while ensuring geometric stability. Figure 2b presents the measured frequency responses of the UA. Due to unavoidable manufacturing tolerances, the resonance frequencies exhibit a maximal dispersion of 100 Hz. The three ultrasonic actuators are mechanically fixed by four tensioning ropes (pretensioned with 30 MPa), as shown in Figure 1b. During the preloading process, two quarter-ring centering components were used to ensure that the central axis of each actuator is precisely aligned with the designated position within the triangular configuration. The positioning accuracy is therefore primarily limited by the machining and assembly tolerances of these centering components, which are within the sub-millimeter range. Since the UA are coupled to the frame solely through an air gap instead of a rigid mechanical connection, this configuration forms an air isolation position between output-surface of

UA and frame that effectively reduce the transmission of high-frequency vibrations. Since the air gap acts as a compliant medium with high damping for out-of-plane motion, the dynamic coupling between the UA and the frame is minimal. As a result, the vibrations of actuator are only weakly transferred to the other components, ensuring minimal mechanical interactions between the individual UAs.

2.3. Structure of Magnetic Actuator

In the hybrid actuator, a magnetic actuator (designed and manufactured in-house at the Institute of Production Engineering and Machine Tools (IFW) in Hannover, Germany) counteracts the levitational force of the UA, thus providing preload to the system. As illustrated in Figure 3b, the magnetic core is designed in a ring-shaped configuration with an inner diameter of 128 mm, a ring width of 20 mm, and a height of 13 mm. The coil is placed in a groove of the U-shaped magnetic core. A large number of windings are chosen to maximize the magnetic field strength for a given current. Moreover, increasing the number of turns raises the coil inductance, allowing for the improved storage of magnetic energy. Consequently, an electromagnet with a higher number of turns can generate considerably stronger magnetic forces at the same current. However, this also increases the electrical resistance and thermal losses, which means that the optimal number of turns must be carefully determined considering this compromise. For the present application, a coil with 56 turns of copper wire with a diameter of 0.75 mm was identified as optimal.

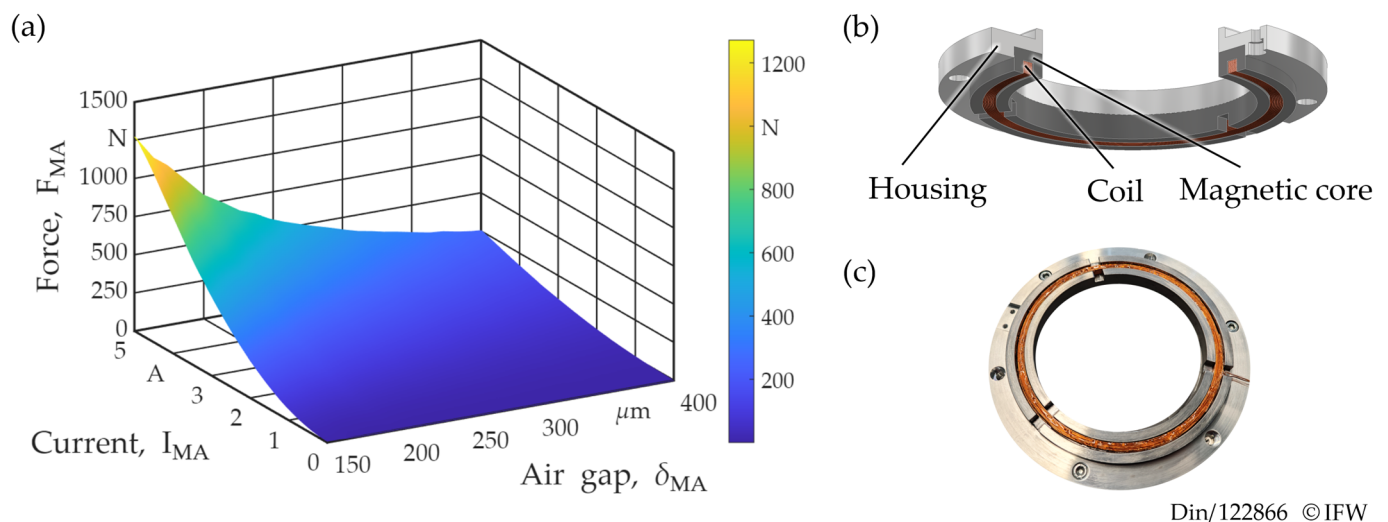


Figure 3. (a) Characteristic field of MA, (b) structure of MA, (c) manufactured MA.

The reluctance force generated by the electromagnet depends on the number of coil turns, the applied current, and the air gap height [10]. In addition, the permeability of the magnetic core (μ_M) and the return yoke (μ_R) significantly influence the magnitude of the reluctance force. Due to the nonlinear behavior of the reluctance force, the MA was experimentally characterized by measuring its magnetic force at various air gap heights and currents. In order to obtain the characteristic curve of the electromagnet, a device equipped with three force sensors was used. The height of the air gap was measured by a capacitive displacement sensor. The back iron is composed of the same material as the guide surface subsequently used in the positioning system. A precise characteristic field capturing the dependencies of magnetic force on air gap height and current enables reliable control of the electromagnetic subsystem. In Figure 3a, the experimentally obtained nonlinear characteristic field (F_{MA} – δ_{MA} – I_{MA}) is shown, which is subsequently interpolated to determine the required magnetic force F_{MA} through the height of air gap δ_{MA} and coil

current I_{MA} . In the actual control implementation, the current output is limited to 0–5 A, and the working air gap is typically around 0.3 mm. The three electromagnetic actuators have identical geometric dimensions, and their coils possess the same inductance (1.1 mH) and resistance (0.9 Ω). Therefore, the characteristic field obtained from one actuator can be equally applied to all three actuators without introducing significant error. The influence of cross-coupling between the actuators is negligible, as each actuator operates in a localized magnetic circuit with minimal magnetic flux influence between neighboring units.

2.4. Structure of Overall Positioning System

The two developed actuators are combined into a hybrid actuator (UA + MA), with the UA providing the levitational force. To stabilize the system with a preload magnetic force, the ring-shaped MA is concentrically mounted around the UA. The attractive force generated by the MA is aligned concentrically with the levitation force of the UA, which facilitates the superposition of both forces without introducing additional torque. To examine the feasibility of the developed hybrid actuators in a guideway application, three hybrid actuators are integrated in a 3-DOF positioning system (Figure 4). By selectively controlling each actuator, fine positioning in the Z-direction, as well as the tilt angles φ and θ , can be achieved. The remaining three degrees of freedom (translations along the X- and Y-axes and rotation about the Z-axis) are mechanically constrained in this article. The air gap heights required for feedback control are individually measured for each of the three hybrid actuators using capacitive displacement sensors (CS1, Micro-Epsilon) with a measuring range of 1 mm and a resolution of 20 nm.

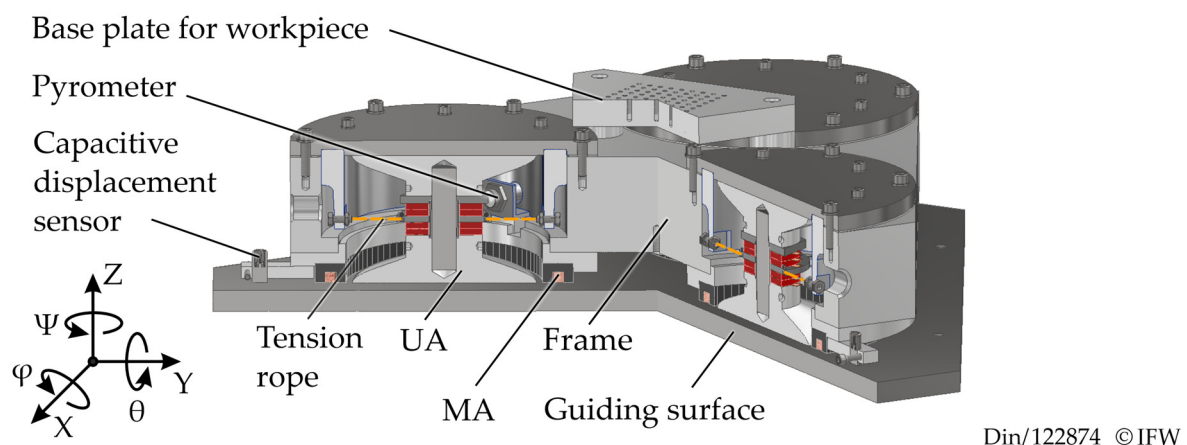
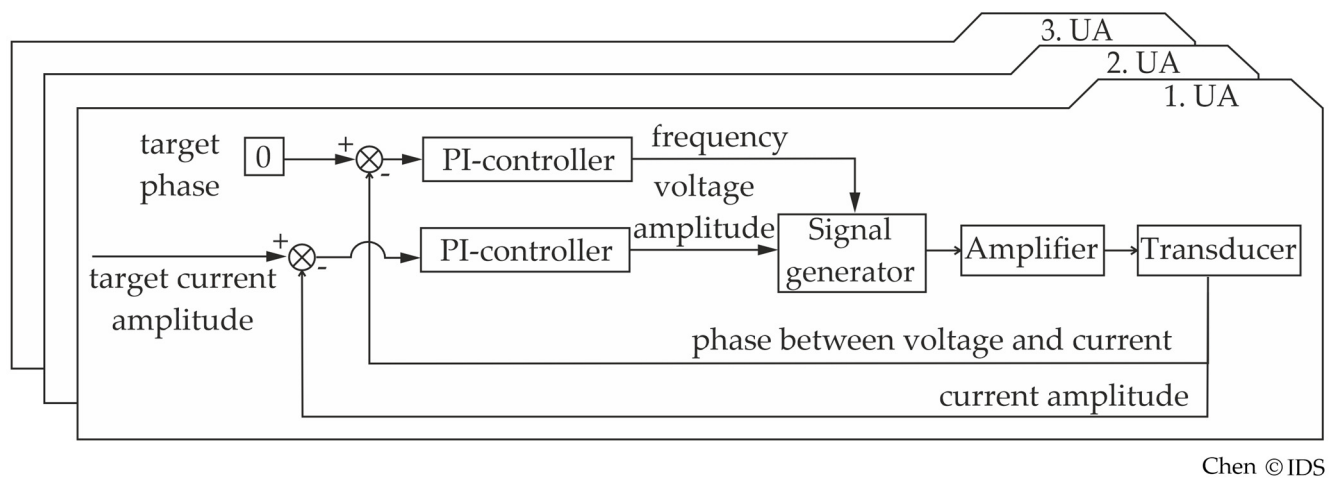


Figure 4. Structure of entire positioning system.

3. Control of the Positioning System

3.1. Control of the Ultrasonic Actuator for Levitation

The control strategy for the designed ultrasonic actuators was implemented using a rapid-control-prototyping (RCP) system (dSPACE). The system currently supports a maximum control loop frequency of 10 kHz. For each of the three UAs, a combined control strategy comprising a phase-locked loop (PLL) and current amplitude control was implemented (Figure 5). The PLL ensures operation at the resonant frequency, thereby maximizing the vibration amplitude. In contrast, the current amplitude control ensures that the vibration amplitude remains constant during operation.

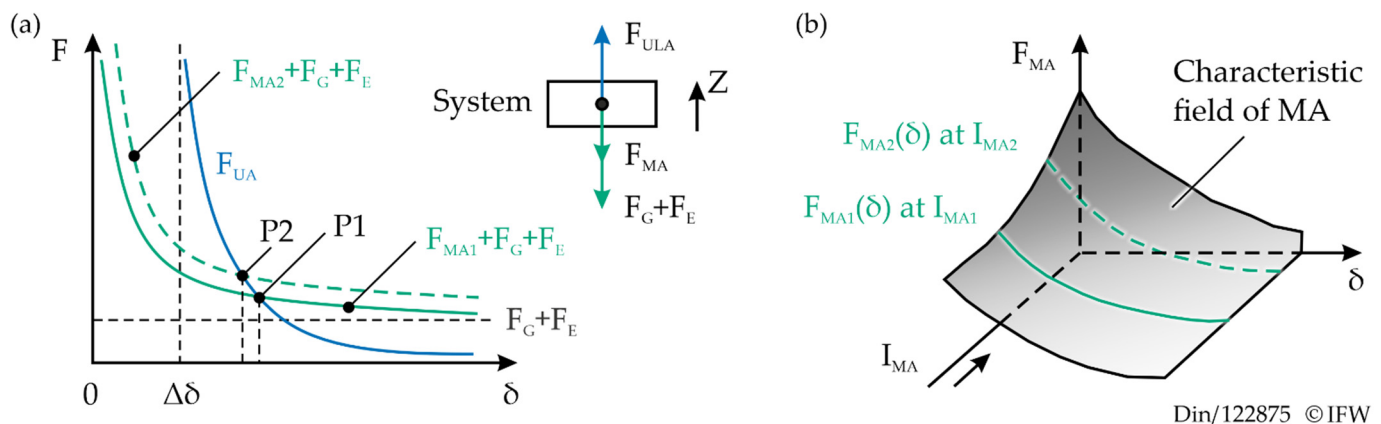


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Figure 5. Control of three ultrasonic actuators.

3.2. Control of the Magnetic Actuator for Positioning

The fundamental control principle of the hybrid actuator's levitation height is based on the superposition of the acting forces. The UA provides the levitation force F_{UA} in the positive Z-direction. It is opposed by the attractive force generated by the MA F_{MA} , the gravitational forces F_G and external forces F_E acting in the negative Z-direction. As shown in Figure 6a, the system reaches an initial equilibrium point P1, where the levitation force balances the gravitational force, external force, and magnetic force. The height difference between the air gaps of the two actuators ($\Delta\delta$ in Figure 1a) determines the lower boundary of feasible equilibrium points.



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Figure 6. (a) Control principle of hybrid actuator, (b) characteristic field of MA.

When the target position is shifted to a lower levitation height, the system must transition to a new equilibrium point P2. In order to achieve this, the magnetic force must be increased by raising the coil current of the MA. In terms of the force map described in Figure 6b, this corresponds to moving from the characteristic curve at current I_{MA1} to a higher characteristic curve at current I_{MA2} . At this increased current, the magnetic force curve intersects with the UA force curve at the new equilibrium point P2. This control principle highlights the cooperative operation of the two actuator types: the UA provides a constant levitation force, while the MA dynamically adjusts its force through current control to establish and stabilize new equilibrium positions.

For the control concept, the highly dynamic MA is applied for position regulation, while the UA is operated at a constant driving power. The control loop in Figure 7 illustrates the positioning algorithm of the system. Starting from the reference vector $Z_{ref} = [Z, \varphi, \theta]^T$

representing the vertical position Z and two tilt angles φ and θ , the control deviation is processed by a PID controller. The corresponding current amplifiers ensure that the required current is supplied to the MAs. The system model serves as the basis for state estimation, which offers the possibility to enhance the robustness against external disturbances.

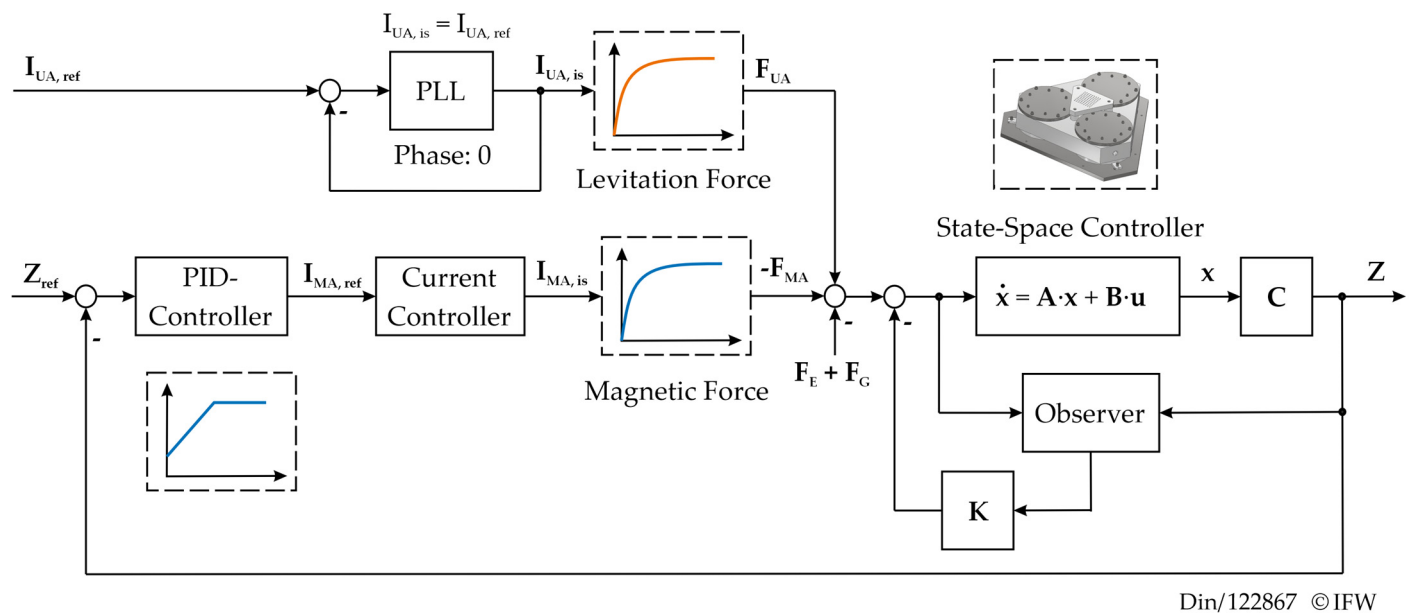
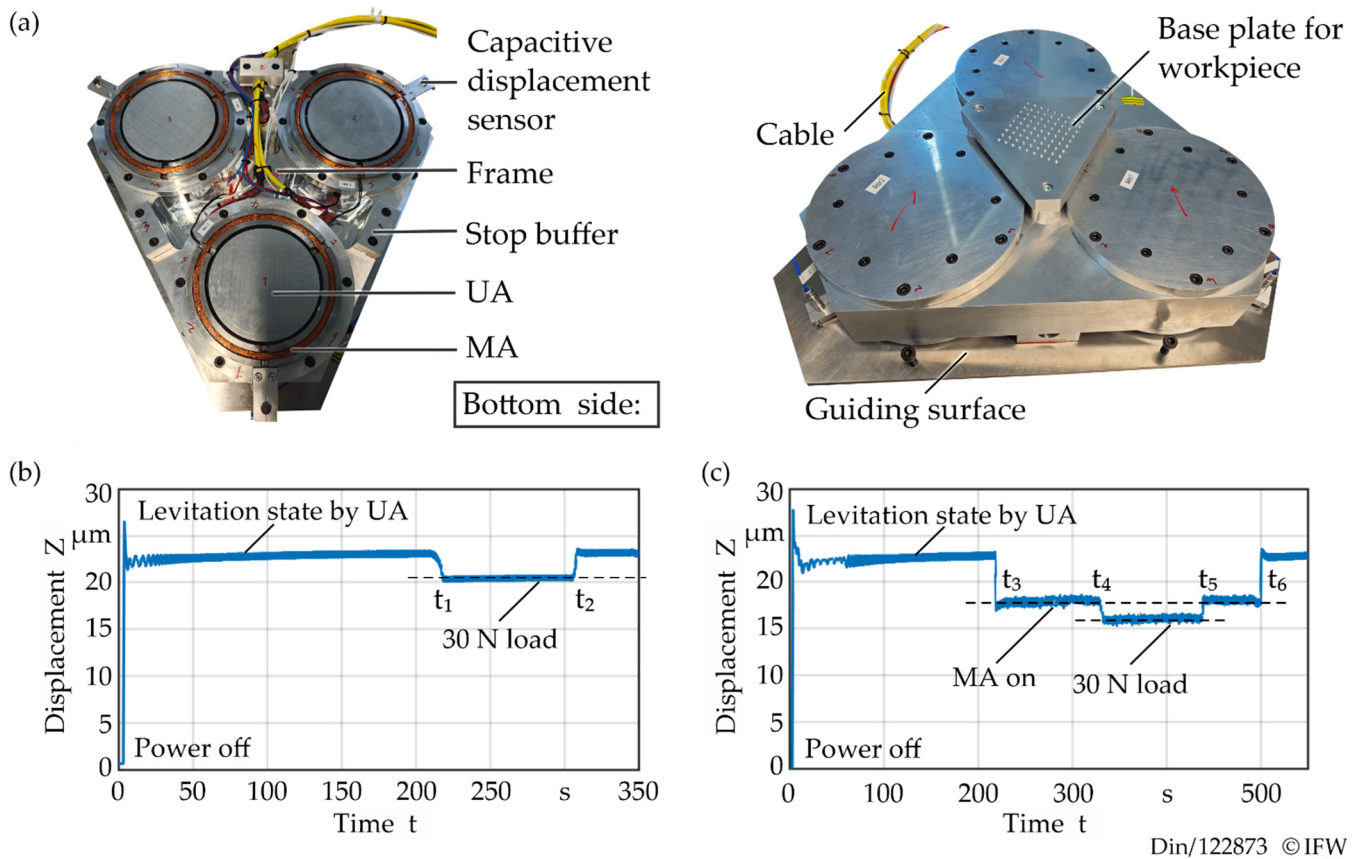


Figure 7. Control strategy of positioning system.

To further improve the control performance, a feedforward strategy based on the experimentally obtained magnetic force map is implemented. This force map quantitatively relates the reluctance force to both air-gap height and coil current, enabling direct computation of the coil current required to generate a desired force. By combining feedforward control with the feedback loop, the system achieves reduced control error, faster transient response, and improved stability. Overall, the structured control loop enables the precise and stable position regulation of the levitated positioning system by combining fast-response magnetic actuators, continuous ultrasonic excitation, and feedforward force compensation.

3.3. Experimental Setup

The experimental setup of the hybrid positioning system is illustrated in Figure 8. The prototype consists of three hybrid actuators, each combining an MA and a UA, which together enable contactless positioning of the slide. For magnetic actuation, three current-controlled electromagnets are driven by dedicated current controllers (Copley Controls JSP-180-30). The UAs are excited using a sinusoidal voltage signal generated from the DDS and amplified by the linear amplifier (QSC RMX5050). The voltage amplitude applied to the UA is controlled via a current amplitude control loop. The voltage level applied to the UA in this paper is about 20 V. The control and coordination of both actuator types are realized via a real-time control platform (dSPACE MicrolabBox), which implements the control algorithms and performs the necessary signal processing.



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Figure 8. (a) established prototype of positioning system, (b) Levitation-state without MA, (c) levitation-state with MA.

4. Results and Discussion

The developed prototype of the hybrid positioning system is shown in Figure 8a. It consists of three hybrid actuators arranged in a triangular configuration. Capacitive displacement sensors are integrated at each actuator position to measure the levitation height with a resolution in the nanometer range. Figure 8b,c illustrate the levitation behavior of the system under load conditions. In Figure 8b, the levitation is solely provided by the UA. The noise level of the measured vertical displacement is around 1 μm because of the interaction of three actuators. When a constant weight of 3 kg (corresponding external load around 30 N) is applied at t_1 , the levitation height is reduced by approximately 3 μm, but stabilizes again at a new equilibrium height. After removing the weight at t_2 , the slide returns to its initial levitation position. This confirms the capability of the UAs to maintain a stable levitation state under load disturbances. In Figure 8c, the MA is additionally activated at t_3 . The magnetic attraction causes the levitation height to decrease by approximately 5 μm, leading to a new equilibrium position. When a 30 N load is applied again at t_4 , the system remains stably levitated and returns to its previous stable status until the load is removed at t_5 . This experiment confirms the controllability of the MA and its potential for active adjustment of the levitation height. For future work, the complete and stable control of three MAs will be further investigated in order to achieve a precise adjustment in three DOF. According to the signals shown in Figure 8a,b, the observed slow increase in the Z-axis displacement over time can be mainly attributed to a gradual temperature rise during operation. As the temperature of the ultrasonic actuator increases, the change in air viscosity and thermal deformation of device lead to a small increase in the levitation height.

From a practical perspective, the external force from the weight of MEMS components processed on such a system is significantly smaller than 30 N. Therefore, the influence of workpiece weight on levitation height and positioning precision can be considered negligible in real applications. In future work, the control capability of the MA will be further examined by implementing advanced control strategies, such as feedforward force compensation or robust controllers, to enhance system stability and disturbance rejection.

5. Conclusions and Outlook

This work presents the design, control, and experimental validation of a novel hybrid positioning system that combines ultrasonic actuators and magnetic actuators to achieve media-free, contactless, and highly precise positioning. The double-acting ultrasonic actuators provide self-stabilizing levitation forces, while the magnetic actuators enable dynamic adjustment of the levitation height and tilt angles by supplying a counteracting magnetic force. The proposed hybrid concept was successfully implemented in a prototype system with three actuators arranged in a triangular configuration. The experimental investigations demonstrated the ability of the system to maintain a stable levitation state under significant external loads of up to 30 N. While the ultrasonic actuator alone was sufficient to sustain stable levitation, the integration of the magnetic actuator enabled active adjustment of the levitation equilibrium, confirming its potential for fine positioning. In practical applications, the weight of MEMS workpieces is considerably smaller than the tested load, indicating that the impact of workpiece mass on levitation stability can be considered negligible.

The hybrid actuation principle offers strong potential for the next generation of precision positioning systems in MEMS manufacturing. Future research will focus on the refinement of the magnetic actuator control and the implementation of advanced control strategies such as robust and adaptive controllers. Since piezoelectric losses lead to thermal expansion of the vibrating body and thereby affect the levitation gap, thermal compensation strategies will be considered. The initial approach is to use the active control of the magnetic actuator to compensate for temperature-induced drift during long-term operation. These modifications are expected to significantly improve the robustness, precision, and applicability of hybrid ultrasonic–magnetic positioning systems in industrial micro-manufacturing environments.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DOF	Degree of Freedom
MA	Magnetic actuator
MEMS	Micro-electro-mechanical system
MPT	Micro-production technology
PLL	Phase-locked loop
RCP	Rapid-control-prototyping
UA	Ultrasonic actuator

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